DEFENCE R&D DÉFENSE

DIINS – The Next Generation CPF Navigation System – An Overview

J.S. Bird
Defence Research Establishment Ottawa

DEFENCE RESEARCH ESTABLISHMENT OTTAWA

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ABSTRACT

The Canadian Navy has been developing a highly fault-tolerant, integrated navigation system for its dual-INS equipped frigates for a number of years. The system, called DIINS (Dual Inertial Integrated Navigation System), is now in the final stages of sea trials before being prepared for installation on the vessels. This report provides a high level overview of the system.

RÉSUMÉ

La marine canadienne a développé un système de navigation intégré fortement insensible aux défaillances pour ses frégates équipées par double-INS depuis un certain nombre d'années. Le système, appelé DIINS (système double de navigation intégré inertiel), est maintenant aux étapes finales des épreuves en mer avant d'être préparé pour l'installation sur les navires. Ce rapport fournit une vue d'ensemble de niveau élevé du système.

EXECUTIVE SUMMARY

The Defence Research Establishment Ottawa has been developing a highly fault-tolerant, integrated navigation system for the Canadian Navy's dual-INS equipped ships for a number of years. The system, called DIINS (Dual Inertial Integrated Navigation System), has undergone extensive sea trials and is now being prepared for fitting on the vessels. Externally, DIINS provides best estimates of ownship navigation data for an ECDIS (Electronic Chart and Display Information System) on the bridge, and for the ship's command and control system. Internally DIINS implements multiple, cooperating Kalman filters to enable the application of sensitive Failure Detection, Isolation and Reconfiguration (FDIR) techniques and to provide high system reliability and navigation accuracy. The sensors being integrated include two inertial navigation systems (INS's), GPS (PPS, SPS and/or differential), speed log, and Loran-C. The application of multiple parallel filters and precise statistical error tests to redundant inertial navigation systems has been very limited until the most recent generations of microprocessors. Such a system is significant in that the design has been optimized for automatic failure detection and reconfiguration and to provide navigation information in decreasing but known accuracy as sensors fail; thus the operator can always be confident that the best remaining sensors are being used to navigate. Such a complex and comprehensive integrated navigation system is quite unique among the world's navies and this program is generating interest among allied nations. This report begins with an overall review of the intent of the DIINS program, and outlines the physical architecture and operator interaction with the system. It then goes into details of the Kalman filter integration and failure detection methods that have been chosen, reviews some sea trial results that have been obtained and briefly discusses the implementation of DIINS within the fleet. Finally, two appendices detail the DIINS output data that is generated for distribution for any user systems on the ship.

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SOMMAIRE

Le Centre de recherches pour la défense Ottawa développe, depuis un certain nombre d'années, un système intégré de navigation à forte tolérance des défaillances pour les navires de la marine canadienne équipés d'un système INS double. Le système, appelé DIINS (système intégré double de navigation par inertie), a subi des essais en mer poussés, et on l'adapte actuellement en vue d'une exploitation à bord des navires. Du point de vue fonctionnel, le DIINS fournit les meilleures évaluations des données de navigation du navire pour le SEVCM (système électronique de visualisation des cartes marines) sur le pont et pour le système de commandement et de contrôle du navire. Du point de vue interne, le DIINS comporte de multiples filtres de Kalman associés permettant l'application de techniques de détection de défaillance, d'isolement et de reconfiguration (FDIR) à sensibilité élevée et offrant une fiabilité et une précision de navigation de niveau supérieur. Les détecteurs intégrés comprennent deux systèmes de navigation par inertie (INS), un GPS (PPS, SPS et/ou GPS différentiel), un loch et un Loran-C. Avant que les plus récentes générations de microprocesseurs aient fait leur apparition, les filtres parallèles multiples et les essais précis d'erreurs statistiques étaient très peu utilisés dans les systèmes redondants de navigation par inertie. Le nouveau système marque un progrès important, car sa conception a été optimisée pour exécuter automatiquement la détection des défaillances et la reconfiguration ainsi que pour fournir de l'information de navigation de précision décroissante mais connue à mesure que les détecteurs tombent en panne. L'opérateur est donc toujours assuré que les meilleurs détecteurs restants sont utilisés pour la navigation. Ce système intégré de navigation, complexe et global, est le seul de son genre dans les marines du monde, et ce programme suscite de l'intérêt chez nos alliés. Le rapport commence par une vue d'ensemble des objectifs du programme DIINS, puis décrit l'architecture matérielle et l'interaction de l'opérateur avec le système. Il donne ensuite des détails sur les méthodes choisies d'intégration des filtres de Kalman et de détection des défaillances, examine certains résultats d'essais en mer et traite brièvement de la mise en service du DIINS à l'intérieur de la flotte. Enfin, deux annexes donnent des détails sur les données de sortie du DIINS, distribuées à tous les systèmes utilisateurs du navire.

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1. INTRODUCTION

1.1. Background

The Defence Research Establishment Ottawa has been developing a highly fault-tolerant, integrated navigation system for the Canadian Navy's dual-INS equipped ships for a number of years. The system, called DIINS (Dual Inertial Integrated Navigation System), has undergone extensive sea trials and is now being prepared for fitting on the vessels. Externally, DIINS provides best estimates of ownship navigation data for an ECDIS (Electronic Chart and Display Information System) on the bridge, and for the ship's command and control system. Internally DIINS implements multiple, cooperating Kalman filters to enable the application of sensitive Failure Detection, Isolation and Reconfiguration (FDIR) techniques and to provide high system reliability and navigation accuracy. The sensors being integrated include two inertial navigation systems (INS's), GPS (PPS, SPS and/or differential), speed log, and Loran-C. The application of multiple parallel filters and precise statistical error tests to redundant inertial navigation systems has been very limited until the most recent generations of microprocessors. Such a system is significant in that the design has been optimized for automatic failure detection and reconfiguration and to provide navigation information in decreasing but known accuracy as sensors fail; thus the operator can always be confident that the best remaining sensors are being used to navigate. Such a complex and comprehensive integrated navigation system is quite unique among the world's navies and this program is generating interest among allied nations. This report begins with an overall review of the intent of the DIINS program, and outlines the physical architecture and operator interaction with the system. It then goes into details of the Kalman filter integration and failure detection methods that have been chosen, reviews some sea trial results that have been obtained and briefly discusses the implementation of DIINS within the fleet. Finally, two appendices detail the DIINS output data that is generated for distribution for any user systems on the ship.

1.2. Overview

DIINS provides integrated navigation data to an electronic chart system by integrating the data from the twin Sperry MK-29 (or 49) INS's with the GPS, DGPS, speed log and other nav-aids onboard Canada's Halifax-class patrol frigates (CPF). This provides an accurate and reliable optimal position estimate that is highly robust with respect to sensor failures. It does this through a scheme of multiple, parallel Kalman filters and a sophisticated Failure Detection, Isolation and Reconfiguration (FDIR) module. DIINS is the product of several years of research and development effort, and is currently in the Advanced Development Model (ADM) phase. The experimental development model (XDM) developed at DREO, has been tested onboard HMCS Calgary, and provided integrated INS/GPS data to drive the chart's displays, if selected to do so by the operator. References [1], [2], and [3] describe DIINS in earlier forms. Ref [4] describes its predecessor MINS (Marine Integrated Navigation System). References [5], [6], [7] and [8] describe the theoretical and algorithmic details of the DIINS internal filtering.

DIINS has been designed to be housed within a bridge-resident electronic charting system called SHINNADS (Figure 1). SHINNADS (Shipboard Integrated Navigation And Display System) is a full Electronic Chart and Display Information System (ECDIS) that is being procured from Offshore Systems Ltd. of North Vancouver B.C. by the Canadian Navy for its main surface fleet. SHINNADS has been designed by the Navy to interface to the CPF's INS, speed log, navigation radar and P/Y GPS receiver, and provides a number of features of interest to the Navy in its software. In addition, an interface to DIINS allows SHINNADS to accept and display the integrated navigation solution from the DIINS processor, which is to be housed in the VME card cage in the SHINNADS console. SHINNADS has both a VME computer that hosts the charting functions, and an OS/2 PC that hosts a number of configuration and file server utilities.

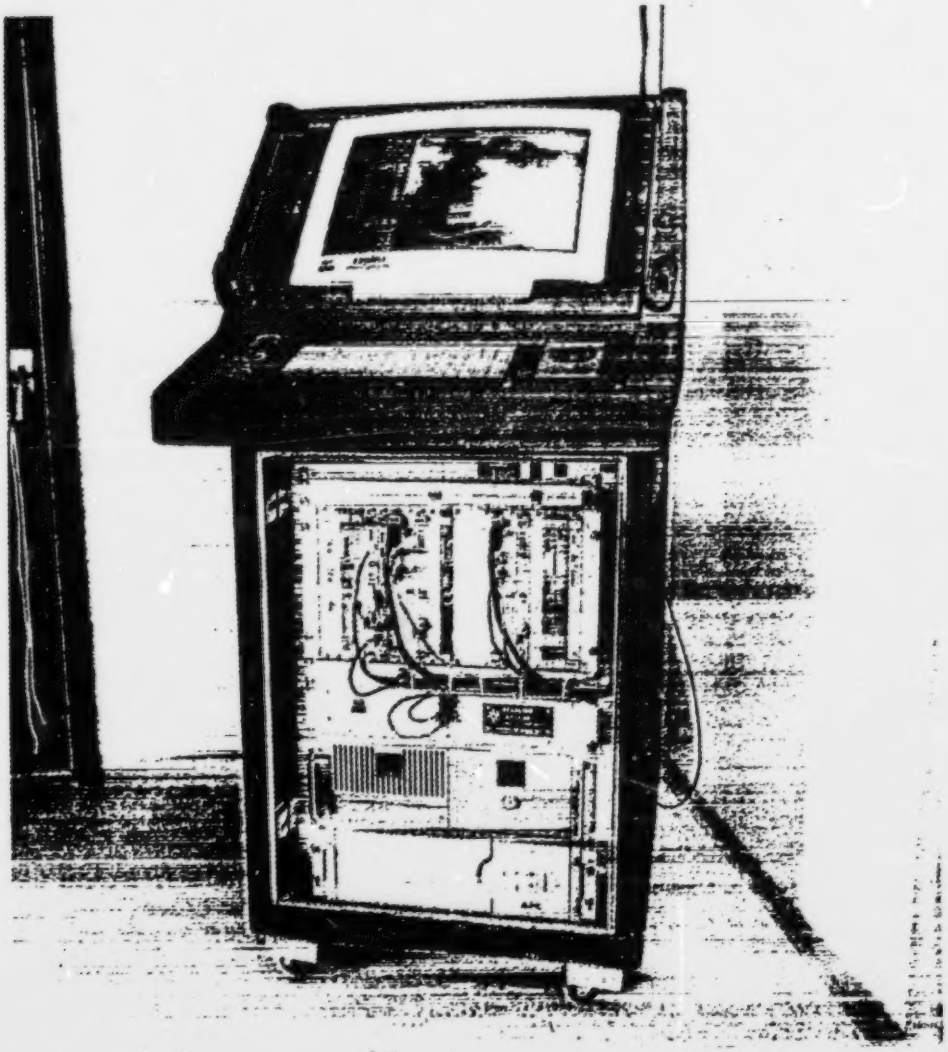

Figure 1: The DIINS/SHINNADS Console

2. MOTIVATION FOR DIINS

Without DIINS, the SHINNADS system typically obtains its navigational information from a commercial differential GPS receiver that is housed within its own console. In a naval environment however, DGPS is generally not considered to be sufficient in many cases. While the accuracy and availability of DGPS is unmatched in friendly coastal areas, navy ships must be equipped to operate in all corners of the world. Commercial GPS and DGPS receivers are vulnerable to jamming and spoofing by hostile forces or by unintentional means. High value naval assets must have reliable and self contained navigation equipment to sustain their combat operations during times of GPS unavailability. In addition, weapons and sensors require high rate attitude information not available from GPS. Thus almost all modern naval warships have dual Inertial Navigation Systems (INS's) that are capable of operating autonomously for long periods of time without external updates. Submarines are an especially important case.

The twin INS's offer redundancy of navigational information in case of catastrophic loss of one of the units. The INS's also provide heading and attitude data that is used throughout the ship in the critical sensor and weapons systems that enable the ship to conduct its operations. Therefore the inertial navigators are considered the heart of the ship's navigation system and the presence of two such units on each ship provides for an excellent opportunity for a highly integrated and robust navigation system. Such a system can configure itself to use the best combinations of sensors available and to continuously monitor the status of all the individual sensors to remove any failed or failing sensors from the navigation solution. Up until this point, the various navigation sensors were often very loosely integrated (or not at all) and full exploitation of the rich, redundant information has not been obtained. The ability to detect, isolate and remove failed sensors from the navigation solution was a primary motivation for the development of the DIINS system.

3. DIINS EXTERNAL ARCHITECTURE

The external architecture of the DIINS/SHINNADS system as implemented on Halifax class ships is shown in Figure 2. The DIINS navigation computer optimally combines data from all the sensors into a single best estimate, while performing sensor error detection. It provides this estimate to the SHINNADS ECDIS display and can distribute the data to other users. SHINNADS also overlays the radar data provided by the navigation radar as well as plotting tracked contacts from the radar's ARPA (automated radar plotting aid) function if available. In SHINNADS systems that do not have the DIINS subsystem, ownship navigation data is provided by an internal DGPS set, complimented by synchro heading and speed available from the ship's synchro distribution system. (It also has a number of other interfaces for ancillary equipment such as anemometers and depth sensors.) The primary sensors that DIINS integrates are the two inertial systems and the P/Y code GPS receiver. DGPS is also used when available. Loran-C is also a viable input and is also used when available. DIINS does have the capability to use ship's speed log, but in the current implementation on the Halifax class ships, it does not use it directly. Rather the inertial systems are "speed log

damped" meaning the log is used as an input to the INS's which use it to damp their internal velocity errors, which would otherwise undergo Schuler oscillations [13].

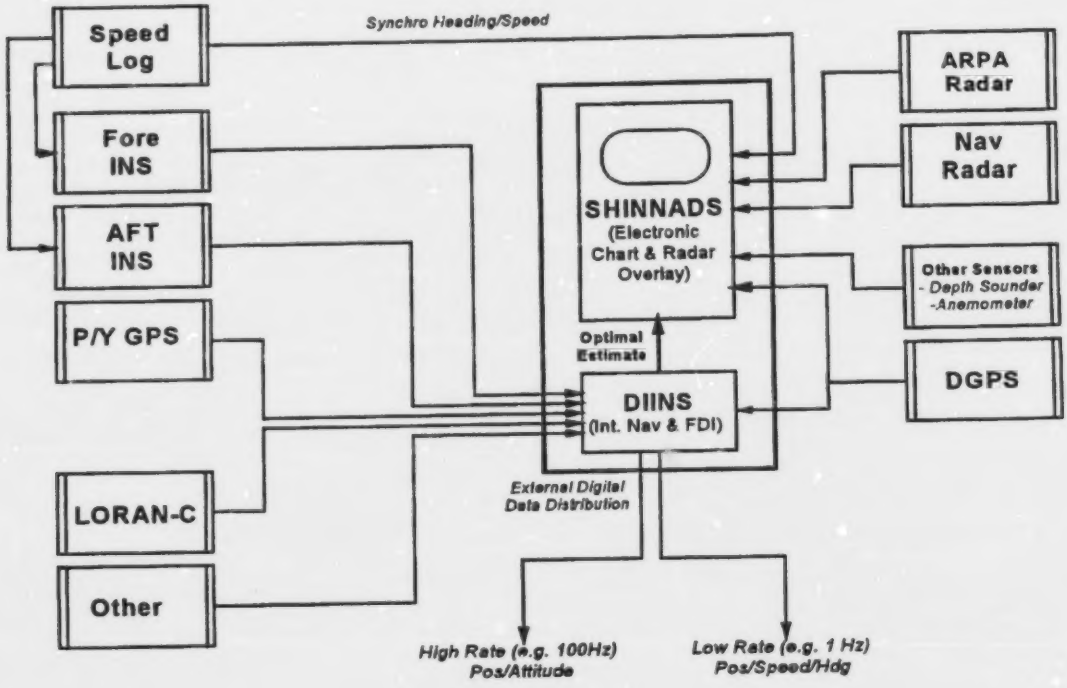

Figure 2: DIINS External Architecture

Physically DIINS consists of 3 VME computer cards that reside in a bridge-resident standup console along with SHINNADS (Figure 1). The primary display is a 21" monitor with keyboard and trackball input. Sensor inputs are typically RS-232/422 or synchro. DIINS computes and sends its optimal navigation output to SHINNADS VME computer via an RS-232 output and accepts configuration commands from the SHINNADS PC computer on another serial port. DIINS incorporates an optional serial output of high rate navigation and attitude data for distribution to other potential users on the ship. A complete description of this output stream is included in Appendix A.

4. OPERATOR INTERFACES

There are two basic operator interfaces through which a user interacts with DIINS. One is the Navigation Display screens that are displayed on the SHINNADS console. The second is the DIINS HCI (human computer interface) program that resides on a PC inside the SHINNADS console. On the console is a simple rocker switch that allows either the VME based Navigation screens or the PC based configuration and setup screens to be shown on the display.

4.1. DIINS Navigation Display Screens

When DIINS is operating in normal fashion within SHINNADS, and the operator has selected DIINS as the position source it is to use, any of the dozen or so SHINNADS screen layouts can be used and the underlying position source will be identified on the screen as DIINS. In addition, two special screens have been designed for use with DIINS that convey more information to the operator. These screens are shown in Figure 3 and Figure 4. Figure 3 shows the DIINS DETAILED screen. The position of the chart is driven by DIINS and the numerical data is displayed in text boxes around the graphical chart. (Appendix B details from where in the DIINS data stream each field on the display obtains its data.)

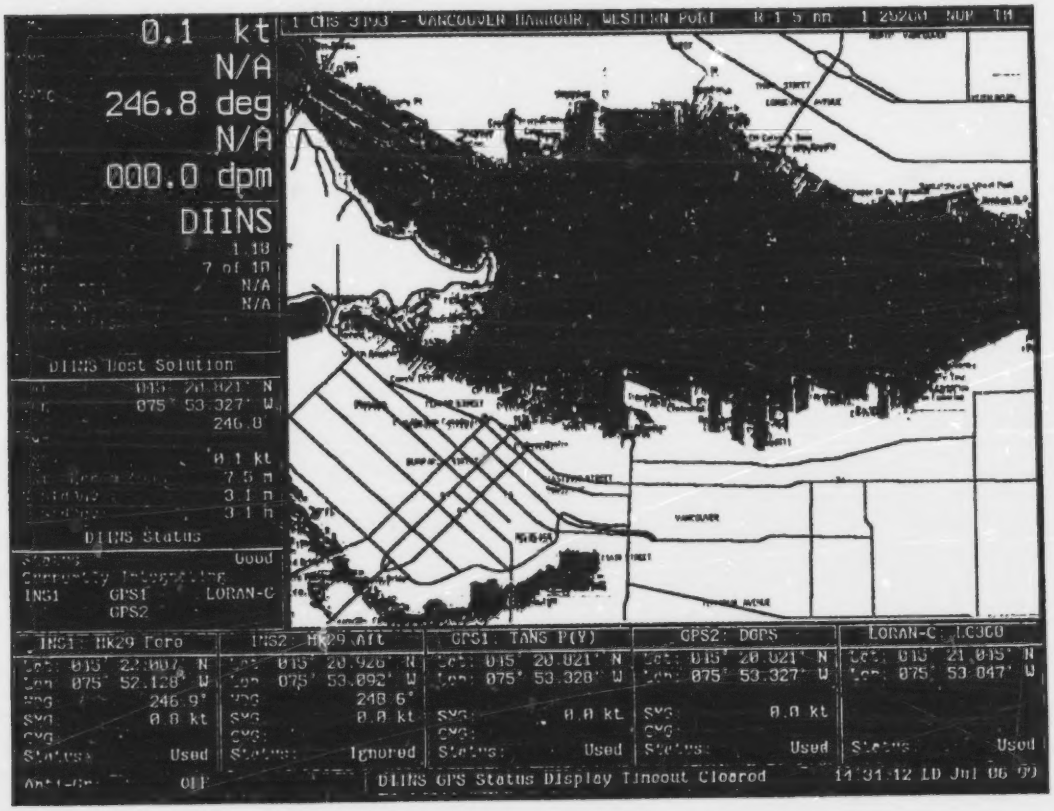

Figure 3: DIINS Detailed Navigation Display

Starting in the upper left corner of Figure 3, the first text box contains a large font with the primary data required to steer the ship: present speed made good (SMG) and course made good (CMG) over ground, present heading (GYRO), water speed (LOG) and rate of turn (ROT). All of these except the Log are from DIINS. Water speed comes directly from the ship's speed log via a syncho interface in SHINNADS.

The next box displays the current position source (DIINS) and some information about the present GPS satellite coverage and differential correction status (These will probably be removed in a later version of this screen as they are not really relevant at this level).

Next is the integrated position solution from DIINS. This is the best available estimate of ownships position and has been arrived at by the DIINS internal Kalman filters which optimally weight the data from each of the position sources. These filters are described in more detail in the next section and are fully described in ref [6]. Also in this box is a display of the estimated accuracy of the blended solution. This is presented in two forms: as North and East standard deviations, and as a 95th percentile circular error probable (CEP). This 95% value indicates that the true position of the ship is, to a probability of 0.95, within a circle of the displayed radius from the DIINS estimated position.

The next box displays the basic DIINS status indicators. The overall Status can be one of three states:

- "Good" - there is at least one good INS and one good Kalman filter operating
- "Single Sensor" - There is no healthy integrating filter (typically because both INS's have failed) and the best available single sensor is being used for output
- Failed - if all available sensors have failed, the display turns red and data is not output until at least one sensor returns to good health.

Also in this box is a list of the sensors that are currently being integrated to determine the blended solution.

Across the bottom are five windows, one for each of the primary navigation sensors - the two INS's, two GPS's and the Loran receiver. In each box is the raw position provided by each sensor, as well as the heading, speed, course and status information from that sensor. These can be used by the operator to visually confirm the reasonableness of each sensor and the blended solution. Generally the DIINS position will be quite close to the GPS positions. Note however, that the DIINS position is by default the center of the ship, and the GPS's report the positions at the antennas which can be several 10's of meters away from ship's center (or a noticeable fraction of an arc minute of latitude or longitude). DIINS correctly accounts for these lever arm distances, and the lever arms can be changed/verified in the DIINS configuration program resident on the PC.

A simpler DIINS display is available, as is shown in Figure 4. The data from the individual sensors is not displayed, leaving more room for the chart. The rest of the data windows are the same as the previous layout.

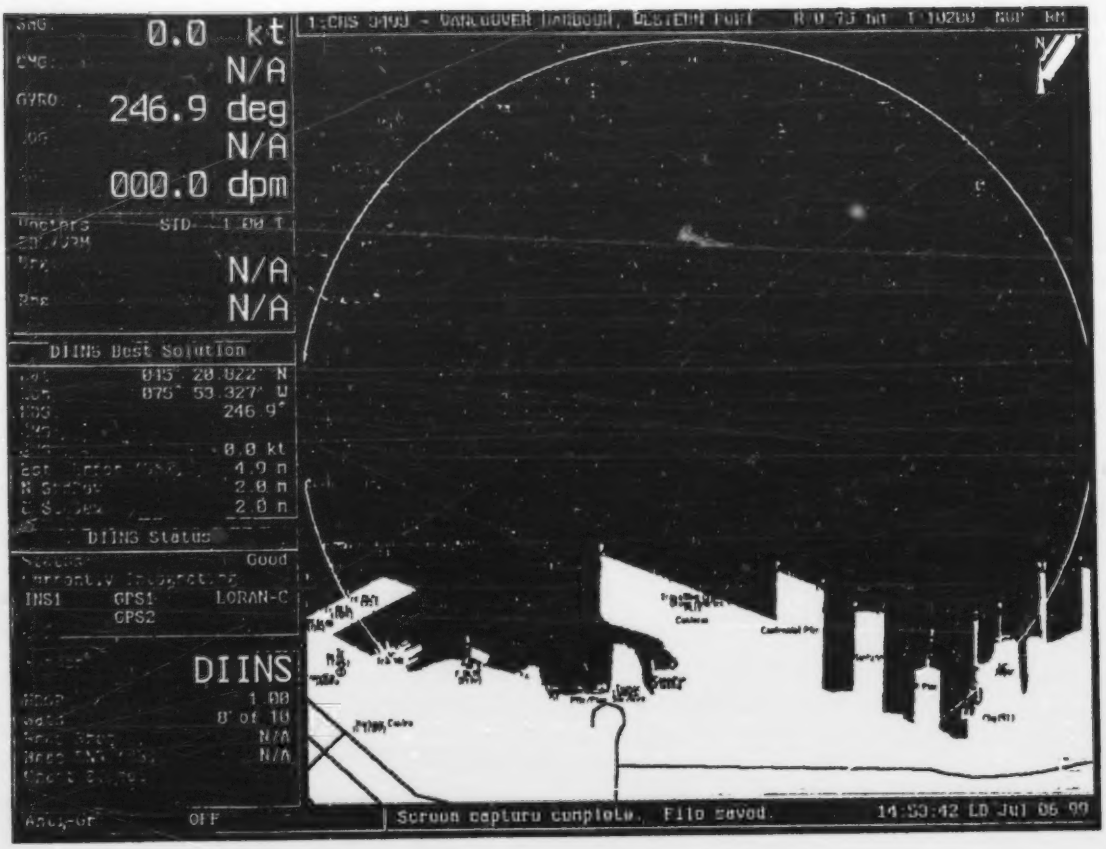

Figure 4: DIINS Simplified Navigation Display

4.2. DIINS HCI Utility

A number of DIINS configuration parameters can by viewed or changed by running a PC based utility program developed for this purpose. The program resides on the OS/2 PC within the SHINNADS console and can be accessed by selecting the PC on the rocker switch on the console and running the program (called DIINS HCI). The initial screen of the DIIINS HCI that is presented to the operator is shown in Figure 5. This program enables the operator to:

- select which sensors are available to DIINS;
- install specific sensors in this DIINS configuration;
- enter the lever arms describing the position of each sensor relative to the reference position;
- select the communications settings (baud rate, etc.) for each sensor;
- change some of the sensor measurement failure detection thresholds;
- enable data logging for onshore post-mission analysis;

- manually disable/enable sensors while DIINS is running (part of SelectSensors) .

All of these features (except for the last one) are changeable only when DIINS first starts up. Only the manual sensor disable/enable can be used after the DIINS Kalman filters are running. To change any of the other parameters, DIINS must be restarted. DIINS can be restarted at sea without restriction. Valid navigation data will be available within minutes of the restart, provided the sensors are operating normally. The Kalman filters quickly converge to their operating values.

There are a number of Kalman filter parameters that cannot be changed by the operator. These parameters, such as gyro bias random walk standard deviations and correlation times, should only be changed as a result of a fine tuning process by a knowledgeable Kalman filter designer. These parameters are stored in non-volatile memory in the DIINS system and can be changed in the laboratory (or onboard with special computer interface hardware).

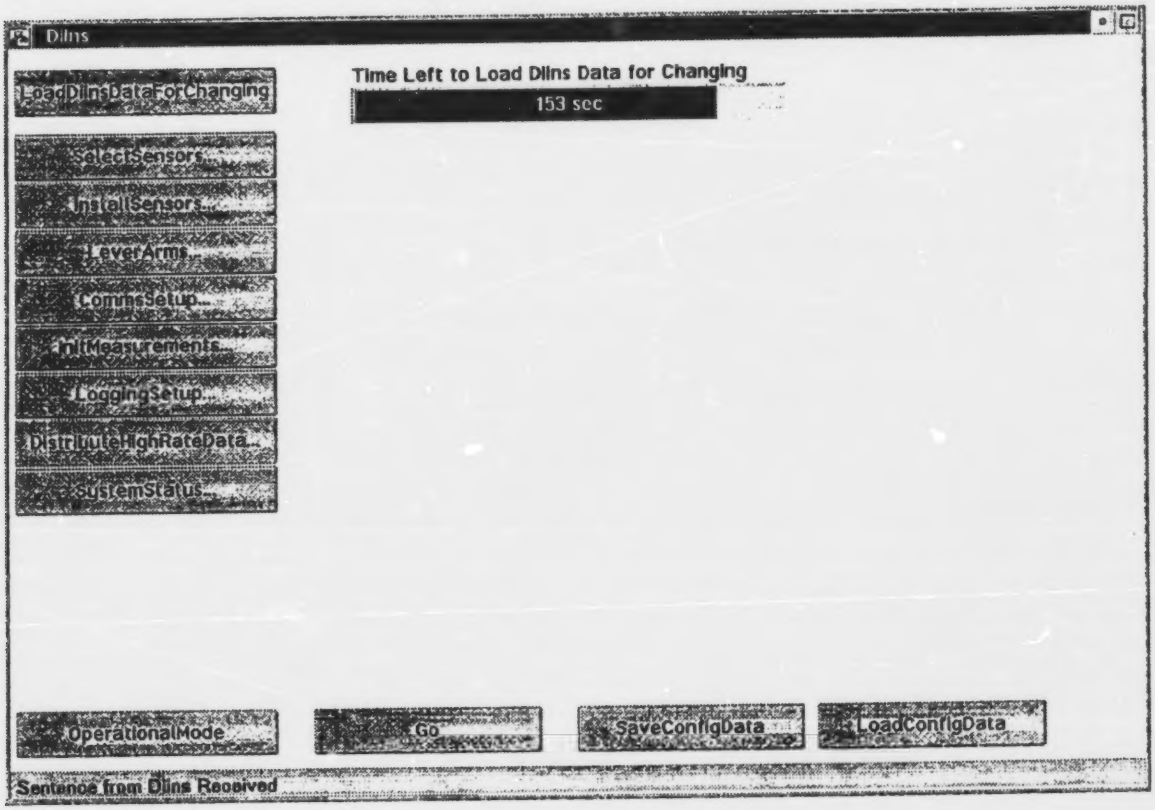

Figure 5: DIINS HCI Setup and Configuration Display

A separate manual regarding the use of the DIINS HCI can be found in Reference [11]

5. DIINS INTERNAL ARCHITECTURE

The DIINS core software has been designed to be as flexible as possible. All of the software has been written in ADA and is highly configurable. Since the core DIINS Kalman filtering software is quite generic, it has the ability to use many more sensors than are available on the ships (GPS attitude being a prime example). The internal architecture of DIINS is not one Kalman filter, but is actually a family of concurrent, cooperative filters arranged in a hierarchy with different subsets of sensors integrated by each filter. Reference [5] describes the internal filtering in full detail. This section summarizes the main features of the internal Kalman filters and the design of the failure detection algorithms in DIINS. A good Kalman filter reference can found in [12].

5.1. Individual Kalman Filters

The filters are error state, extended Kalman filters, each typically estimating the errors in one of the two inertial systems by using the data available from one or more of the aiding sensors (GPS, speed log, etc.).

Each filter has a state vector of the form:

$$\vec{x} = [\vec{x}_{INS_{1or2}} \vec{x}_{Aid_1} \cdots \vec{x}_{Aid_n}]^T$$

The state vector for each filter differs slightly as they each integrate different subsets of the sensor suite. The DIINS Kalman filters can model either gimballed or strapdown platform INS's and use a psi-angle error formulation. The INS states are error states consisting of position error ($\vec{\tilde{r}}$), velocity error ($\vec{\tilde{v}}$), and attitude error ($\vec{\psi}$), as well as 3 gyro bias ($\vec{\varepsilon}_G$) and 2 (or 3) accelerometer bias ($\vec{\varepsilon}_A$) Markov states (depending on the INS mechanization):

$$\vec{x}_{INS} = [\vec{\tilde{r}} \quad \vec{\tilde{v}} \quad \vec{\psi} \quad \vec{\varepsilon}_A \quad \vec{\varepsilon}_G]^T$$

The aiding sensor states for the GPS, DGPS and Loran receivers are modelled as exponentially correlated Markov processes, with the GPS having 2 position error and one time lag Markov states:

$$\vec{x}_{GPS} = [\tilde{r}_x \quad \tilde{r}_y \quad \tau_{gps}]^T,$$

and Loran having 4 time difference error Markov states (converted to equivalent range difference errors, $\Delta\tilde{s}$), one for each pair of stations in the chain:

$$\vec{x}_{LORAN} = [\Delta\tilde{s}_{TDw} \quad \Delta\tilde{s}_{TDx} \quad \Delta\tilde{s}_{TDy} \quad \Delta\tilde{s}_{TDz}]^T.$$

The measurements for the filters consist of misclosures. These are defined as the differences between the aiding sensor and the INS sensor used in that filter. For example, a position measurement from an aiding sensor minus the current INS position is the measurement that is used in the Kalman filter:

$$z_y = y_{Aid} - y_{INS}$$

Velocity measurements are handled similarly. Care is taken to ensure that all measurements are converted to consistent coordinate frames and that all lever arms are properly accounted for before they are used in the simple difference equations of this type. This is done so that the matrix representing the relationship between the measurements and the states (the "*H*" matrix) is relatively simple (generally linear time invariant). This significantly simplifies the propagation of the filter covariance matrix. The tradeoff is the extra pre-processing required on the measurements before they are differenced. All DIINS Kalman filters are numerically stable UDU^T formulations.

5.2. Failure Detection, Isolation, And Reconfiguration (FDIR)

The FDIR algorithm in DIINS is the key to system reliability. Reference [6] describes this in full detail. The basic design philosophy is to have multiple, simultaneous, independent Kalman filters to ensure that for every possible failure, there is at least one filter which is uncorrupted by the failure. The internal architecture of DIINS filtering scheme is shown in Figure 6.

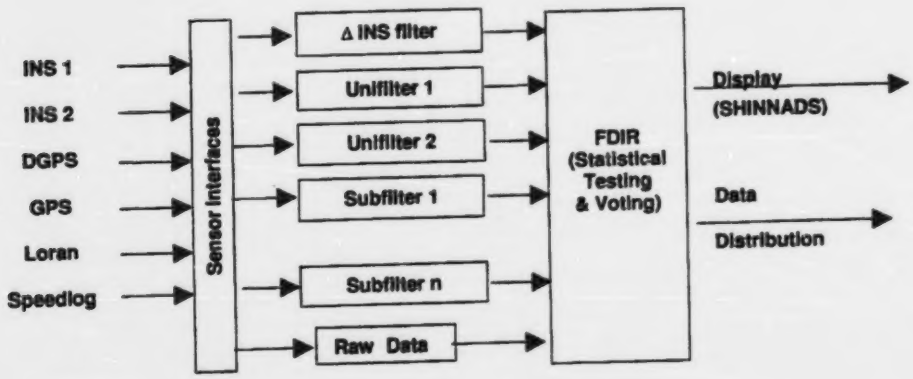

Figure 6: DIINS Internal Architecture

The filters shown in Figure 6 require some explanation. The Kalman filters are arranged in a parallel fashion and operate concurrently. Each filter, except the ΔINS filter, integrates an INS with a different subset of the aiding sensors. As an example, consider a configuration of two INS's, one GPS receiver and one Loran-C receiver. In this case there are 7 filters, as listed in Table 1. The first filter, which integrates the two INS's, is used only to assist in INS failure isolation and not used for navigation. The two unifilters each integrate one of the INS's with all of the aiding sensors. The 4 subfilters each integrate one of the INS's with all but one of the aiding sensors. Note the filter "Designation", *FI-J*, refers to the filter based on INS *I* using all aiding sensors but *J*. The FDIR algorithm has the responsibility of monitoring the health of all the filters and the individual sensors and of selecting the 'best' filter for output.

Table 1: Filters in a Dual INS, one GPS, one Loran configuration

No.	*Filter Type*	*Filter Designation*	*Sensors*
1	ΔINS	F0	INS1, INS2
2	Unifilter	F1	INS1, GPS, Loran
3	Unifilter	F2	INS2, GPS, Loran
4	Subfilter	F1-2	INS1, GPS
5	Subfilter	F2-2	INS2, GPS
6	Subfilter	F1-1	INS1, Loran
7	Subfilter	F2-1	INS2, Loran

As stated previously, the primary role of DIINS is for sensor failure protection and it uses its traditional navigation Kalman filters to obtain this. There are two classes of failures, and DIINS takes separate approaches to detect and isolate them. The first class is called ***hard failures***. These are the sudden and rapid failures of sensors that are not uncommon, for example when a sensor suddenly provides no data or obviously incorrect data. The second class is called ***soft failures***. These are characterized by slowly degrading sensor performance. For example an INS accelerometer bias that slowly grows out of spec can cause unreliable INS data if allowed to continue. In a Kalman filter integration system such as this, the filter will actually force the effect of the failure into inappropriate filter error states. In fact a soft failure may be more accurately defined as the result of unmodelled errors which are large enough to corrupt the filtered results but cannot be identified by hard failure detection techniques. Soft failures are almost exclusively associated with inertial systems, primarily because of their dependence on sensitive and finely tuned gyroscopes and accelerometers that are particularly affected by factors such as temperature and gravity fluctuations.

5.2.1. Hard Failure FDIR

Hard failure detection techniques rely on traditional Kalman filter measurement residual testing methods. Residual tests can be thought of as "reasonableness" or "consistency" tests on the raw sensor data. These will eliminate the spurious data that from time to time show up in sensor data. Any data that does not pass the residual test is not used in any of the filters that use that sensor and, in addition, a counter is incremented for that sensor. If *X*% of the sensor measurements over *Y* seconds fail the residual test, then that sensor is considered to have suffered a hard failure and is removed from the navigation solution and the operator is notified. *X* and *Y* are numbers chosen by the filter designer, but can be adjusted by the operator via the DIINS HCI. If the sensor resumes healthy operation and passes the residual test *XX*% of the time over the next *YY* seconds, the failure is considered to have been fixed and the sensor is considered healthy and can resume participation in the navigation solution. There are many subtleties in the actual implementation that cannot be described in full detail here but the following overview describes the sequence of events in the hard failure FDIR process.

5.2.1.1.Hard Failure Detection

First, measurements are not used if the sensor involved passes a bad status flag or other indication that the sensor is not operating properly, or if the time stamp on the data indicates it is too old to perform reliable extrapolation to the current time. Next a Kalman filter residual is computed and tested against statistically expected limits. The basic idea is as follows: The Kalman filter measurements are actually differences between aiding sensor and INS data (sometimes called *misclosures*). For a particular parameter ρ (longitude, for example), the measurement z_ρ is computed as

$$z_\rho = \rho(Aid) - \rho(INS)$$

A Kalman filter residual, $\vec{\upsilon}$, is defined as the difference between the measurement and the filter's predectied value of the measurement based on all previous data:

$$\vec{\upsilon} := \vec{z} - H\hat{\vec{x}}$$

where $\hat{\vec{x}}$ is the current Kalman filter state estimate, and $\vec{z}$ is the measurement vector which is related (via a linear matrix H) to the true state vector $\vec{x}$ through the measurement equation

$$\vec{z} = H\vec{x} + \vec{\varepsilon},$$

where $\vec{\varepsilon}$ represents the measurement noise. The residual covariance matrix is a byproduct of the Kalman filtering:

$$\mathrm{E}\{\vec{\upsilon}\vec{\upsilon}^T\} = \mathrm{E}\{(\vec{z} - H\hat{\vec{x}})(\vec{z} - H\hat{\vec{x}})^T\} = HPH^T + R$$

where $P := \mathrm{E}\{\hat{\vec{x}}\hat{\vec{x}}^T\}$ is the covariance matrix of the state estimate computed by the Kalman filter and $R := \mathrm{E}\{\vec{\varepsilon}\vec{\varepsilon}^T\}$ is the covariance matrix of the sensor measurement noise specified by the system designer. The test to determine if a residual is within statistically significant bounds is

$$[\vec{\upsilon}\vec{\upsilon}^T]_{ii} \le m^2 \mathrm{E}\{\vec{\upsilon}\vec{\upsilon}^T\}_{ii} = m^2[HPH^T + R]_{ii}$$

where m is an empirically selected integer typically in the 3-5 range, and the ii subscript represents the iith element of the matrix. In practice measurements are processed individually, so the actual residual test reduces to the scalar inequality

$$|\upsilon_\rho| \le m\sigma_\upsilon$$

where $\sigma_\upsilon^2 = (H_\rho P H_\rho^T + R_\rho)$. When m=3, this corresponds to approximately a 99% confidence level: that is, 99% of the residuals should fall within ±3σ. In practice, m=5 is often used to reduce the risk of false alarms and to account for the fact that residuals are seldom truly statistically normal, as assumed in classical Kalman filter derivations.

5.2.1.2.Hard Failure Isolation

Hard failure isolation (HFI) requires that the results from 2 or more filters be compared. This is because any particular residual is formed from the difference of an INS and an aiding sensor measurement. Thus if a residual fails, it cannot be immediately determined whether the INS or the aid is to blame. For each sensor, a group of hard failure isolation filters is chosen (the selection of these filters is done internally by DIINS using heuristic algorithms created by the system designers). A hard failure isolation is declared only when all designated HFI filters signal the failure. Recovery from a hard failure is declared as soon as any HFI filter recovers.

The selection of which filters to use for HFI relies on the following general principles:

- The two filters judged to be the most effective for HFI for each sensor will be used for isolation. More than two can increase the time to isolation.
- The hard failure of any aiding sensor is best detected using filters which use that sensor as well as the most accurate healthy sensor
- The hard failure of any INS is best detected using the ΔINS filter and the filter which uses only the failed INS and the most accurate healthy aiding sensor. If the ΔINS filter cannot be used (if the other INS has already failed), then select the filter that uses only the most accurate healthy aid and the one that uses only the second most accurate healthy aid.

In addition, filters which have detected a "soft failure" (discussed in the next section) will not be used for HFI since their state estimates are not considered reliable. As an example of hard failure isolation, consider the two INS, two aiding sensor example (GPS and Loran) in Table 1. If we think of the 7 filters in a "tree" structure with the ΔINS filter at the top, with the left and right sides of the tree containing the filters associated with each INS, we obtain a picture like Table 2 below.

Table 2: DIINS Filter Tree in terms of Filter Designation Numbers

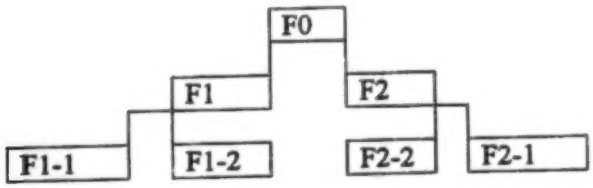

Table 3 illustrates the isolation of hard failures for each of the INS's and the two aiding sensors. In the table, X indicates that filter is used in the hard failure isolation procedure and 0 indicates that filter is not used to isolate a hard failure for that sensor. For example, to isolate an INS2 hard failure, use residuals from filters F0 (the ΔINS filter) and F2-2 (the INS2+GPS filter). To isolate a Loran failure, use Loran measurement residuals from the two unifilters F1 (INS1+GPS+Loran) and F2 (INS2+GPS+ LORAN).

Table 3: Hard Sensor Failure Isolation Table

Hard Failure	F1-1	F1-2	F1	F0	F2	F2-2	F2-1
INS1	0	X	0	X	0	0	0
INS2	0	0	0	X	0	X	0
GPS	0	0	X	0	X	0	0
Loran	0	0	X	0	X	0	0

The situation becomes more complex when more than one failure occurs. For example, after one of the INS's has already suffered a failure, HFI for that INS is suspended and HFI for the remaining sensors use the three filters which do not use the failed INS. If another sensor fails after the first INS, no subsequent failure isolation is possible. (If the other INS fails, there will be no filter with a healthy INS, and thus no filters available for HFI. If either of the remaining aids fails there will be only one filter which does not use a failed sensor. This filter would be used for output and failure detection is still possible, but there is no redundancy left to allow further isolation.) The DIINS FDIR algorithm has been programmed with heuristic logic such as this for all foreseeable hard failure sequences. It is not possible to describe all the scenarios here; full details are described in [6]

5.2.2. Soft Failure FDIR

Soft failures are much more difficult to detect and by definition cannot be detected by residual tests. The definition states that filter results will be corrupted by the effects of a soft sensor failure, *i.e.*, filter performance may be worse than expected, but that the effects of a soft failure cannot be detected by hard failure detection techniques such as residual tests. Various techniques have been proposed in the literature, and the method that was ultimately chosen for DIINS is based on the χ^2 ("chi-squared") model similar to the one described in [9] and [10]. In brief, the test is based on a comparison between two Kalman filter solutions: one is the usual filter with regular measurement updates from independent sensors; the second solution uses the same initial conditions and propagation models but does not perform any measurement updates. A statistical test (based on the χ^2 distribution) looks for unexpected differences in the two solutions. A statistically significant difference triggers an assumption that the filter has experienced a soft failure of any one of its component sensors. Again, the results from multiple filters are used for soft failure isolation (SFI). The basis of the χ^2 test is summarized here.

5.2.2.1.Soft Failure Detection

The Kalman filter propagation model from time t_{k-1} to t_k is

$$\vec{x}_k = \Phi_{k,k-1}\vec{x}_{k-1} + \vec{w}_{k-1},$$

with a corresponding measurement model

$$\vec{z}_k = H_k\vec{x}_k + \vec{v}_k .$$

The vectors $\vec{w}$ and $\vec{v}$ are assumed to be independent, zero mean, Gaussian white sequences with covariance matrices Q and R respectively. The initial state vector $\vec{x}_0$ is assumed to be a Gaussian vector independent of $\vec{w}$ and $\vec{v}$ with covariance P_0. Both filters are initialized to

$$\hat{\vec{x}}(t_0) = \mathrm{E}[\vec{x}(t_0)] = \vec{x}_0$$
$$P(t_0) = P_0$$

State estimates for the filters are propagated according to

$$\hat{\vec{x}}_k(-) = \Phi_{k,k-1}\hat{\vec{x}}_{k-1}$$
$$P_k(-) = \Phi_{k,k-1}P_{k-1}\Phi^T{}_{k,k-1} + Q_{k-1}$$

This is the only step used for the no measurement filter. When a sensor measurement is available, the other filter is updated using

$$\hat{\vec{x}}_k(+) = \hat{\vec{x}}_k(-) + K_k(\vec{z}_k - H_k\hat{\vec{x}}_k(-))$$
$$P_k(+) = (I - K_kH_k)P_k(-).$$

This is the step that differentiates the two filters. (Here (+) indicates the updated estimate and (-) indicates a propagated estimate just before an update.) To describe the χ^2 test, define the state estimates from the two filters as $\hat{\vec{x}}_1$ and $\hat{\vec{x}}_2$, for the filter with and without measurements, respectively. The difference of the two is defined as

$$\vec{\beta} := \hat{\vec{x}}_2 - \hat{\vec{x}}_1.$$

Since both state error vectors are assumed to be standard normal, $\vec{\beta}$ is standard normal as well. Its covariance is

$$\begin{aligned} B &:= \mathrm{E}[\vec{\beta}\vec{\beta}^T] \\ &= \mathrm{E}[\hat{\vec{x}}_1\hat{\vec{x}}_1^T - \hat{\vec{x}}_1\hat{\vec{x}}_2^T - \hat{\vec{x}}_2\hat{\vec{x}}_1^T + \hat{\vec{x}}_2\hat{\vec{x}}_2^T] \\ &= P_1 - P_{12} - P_{21} + P_2 \end{aligned}$$

Under conditions of optimal filter gains, identical state models and identical initial conditions, it can be shown that $P_{21} = P_{12}^T = P_1$ so that

$$B = P_2 - P_1.$$

The χ^2 test for soft failure detection is performed on a test statistic which is the scalar quadratic form of $\vec{\beta}$:

$$b^2 := \vec{\beta}^T B^{-1}\vec{\beta}.$$

The quadratic form of a standard normal vector such as $\vec{\beta}$ has a χ^2 distribution with m degrees of freedom where m is the row dimension of $\vec{\beta}$. The probability that b^2 is greater than some value, χ^2_m, is

$$\mathrm{P}\{b^2 > \chi^2_m\} = \alpha$$

where α is the significance level. Thus whenever

$$b^2 > \chi^2_{m,\alpha}$$

a chi-squared failure (i.e. soft failure detection) will be declared. A careful choice of α is required to balance the risk of false alarms against missed detections. Typically values between 1 and 5 percent are appropriate.

In the DIINS implementation of the soft failure detection test, some heuristic adjustments have been made. First only a portion of the state vector is used to compute $\vec{\beta}$. The selection of the subset to be used was made on the basis of empirical knowledge, testing with real data, and the desire to minimize computational requirements. Some of these results were presented in [3]. It was found that using only the INS system states (defined as the position, $\vec{\tilde{r}}$, velocity, $\vec{\tilde{v}}$, and attitude, $\vec{\tilde{\psi}}$, states) and not using the other sensor error states (gyro/accelerometer biases, aiding sensor Markov states, etc.) was the best choice. The reasons for this are given in brief: Using the full state vector caused significant computational burdens and also seemed to result in many missed detections (the effect of the soft failure was 'diluted'). Excluding the INS system states and using only the sensor bias, etc. states seemed to result in a high false alarm rate (slightly mismodelled error behaviour may be interpreted as a failure). Using all the system states and only the system states produced the best balance. This seems reasonable when one realizes that sensor error states are propagated into system states. Thus a sensor failure (e.g. gyro bias shift) which may first be reflected in the sensor error states will, after some delay, be observable in the system states (attitude tilt, position drift). This helps to reduce false alarms by 'smoothing out' transient unmodelled effects. Similarly it was found that only using position error states, and excluding velocity and attitude errors, produced more missed detections - too much smoothing delays or prevents soft failure detection.

5.2.2.2.Soft Failure Isolation

Soft failure isolation (SFI) is similar to hard failure isolation in that results from more than one filter are used, that for each filter a set of soft filter isolation filters is selected, that a SFI is declared only when all SFI filters signal the failure, and that recovery from a soft failure is declared as soon as any SFI filter recovers. However, whereas the residual tests used in hard failure detection always identify two suspect sensors, the chi-square test used for soft failure detection identifies at least two and probably more, depending on the number of aiding sensors in the particular filter. (Recall the soft failure detection algorithm uses a scalar statistic from a filter, so the entire filter is tested as a whole.) The FDIR processor in DIINS is responsible for collecting the χ^2 test results from each filter, selecting the set of SFI filters for each sensor and determining when a sensor has failed and when it has recovered.

As an example, consider an INS that undergoes a soft failure. Each filter that uses that INS will start a timer when the χ^2 test begins to fail. As soon as the timer reaches a predefined limit (and the chi-square test is still failing), each filter notifies the FDIR processor. When all the failing INS's SFI filters have done so, the FDIR processor will declare the INS soft failure. If the failure is corrected, the failure isolation process is reversed: the χ^2 tests start passing, after predefined delays the filters notify the FDIR processor, and the INS is consid-

ered recovered. Similar to hard failure isolation, SFI will not be declared for a sensor which is currently suffering a hard failure or which is not used in at least two filters.

The selection of filters to use for SFI for each sensor is complex but follows these basic principles:

- More than one filter is required;
- SFI is more reliable when filters using the minimum number of sensors (one INS and one aid) are used;
- INS soft failures are best detected with the ΔINS filter as well as the filter which uses only the failed INS and the most accurate healthy aiding sensor;
- Aiding sensor soft failures are best detected with filters which use only the failed sensor and an INS (additional aids tend to dilute the test);
- When only one INS is available, both filters must be selected from the good INS's branch of the filter tree. Here the choice is less clear, but when possible the filter that uses the INS and all available aids is selected, along with the one that uses only the INS and the failing aid. The process is less reliable in this case.

As an example of soft failure isolation, consider the same set of sensors and filters of Table 1. The filters that are used to declare a soft failure in each of the sensors are illustrated in Table 4.

Table 4: Soft Sensor Failure Isolation Table

Soft Failure	F1-1	F1-2	F1	F0	F2	F2-2	F2-1
INS1	0	X	0	X	0	0	0
INS2	0	0	0	X	0	X	0
GPS	0	X	0	0	0	X	0
Loran	X	0	0	0	0	0	X

In Table 4, FI and FI-J are as defined in Table 1, "X" indicates the filter failed the chi-squared test, and "0" indicates the filter is not used in the isolation process for that sensor. Thus to isolate an INS1 soft failure, the results from the F0 (ΔINS) filter and the F1-2 (INS1+GPS) filter are used: both must fail their chi-square tests for a sufficient amount of time before the INS failure is declared.

What happens after INS1 has already failed? In that case only the filters containing INS2 and aiding sensors are available and the soft failure isolation process then uses the results from the filters of Table 5.

Table 5: Soft Failure Isolation Table after INS1 failure

Soft Failure	F1-1	F1-2	F1	F0	F2	F2-2	F2-1
INS1					0	0	0
INS2					0	X	X
GPS					X	X	0
Loran					X	0	X

5.3. Output Filter Selection

To be truly useful, the results of the FDIR process must be used to identify unreliable filters, to protect uncorrupted filters from the effects of sensor failures, and to select the 'best' filter to be used for navigation. A technique called *filter classification* is used in DIINS to rank the filters according to sensor and filter status and use the highest ranking filter as the source of output to drive the electronic chart display and provide navigation data. Selection of the best source for output is based on a combination of reliability and accuracy. The FDIR process is used to judge filter and sensor reliability and *a priori* knowledge is used to help rank filters according to accuracy. Individual filters in DIINS are not reconfigured on the fly as sensors fail and recover; rather the filters/sensors are flagged as failed and a filter selection algorithm chooses from the currently healthy filters.

A filter is considered for output only if it is not the ΔINS filter, has a good INS, and has not failed the chi-squared test. Of those filters that are judged to be candidates for filter output, the FDIR processor selects the one that has the lowest estimated radial position error standard deviation (from the Kalman filter covariance estimates). If more than one filter have similar accuracy estimates, then the one which has the largest number of healthy aiding sensors is selected. In the case when both INS's have failed and there are no Kalman filters considered reliable, DIINS outputs the navigation data from the most accurate healthy aiding sensor. In the truly worst case when there are no sensors that are considered healthy, DIINS continues to search for the "least unhealthy" sensor (e.g., one that is still supplying data even though it may currently be flagged as suffering a soft failure). Of course the operator is notified of all such circumstances.

6. REPRESENTATIVE DIINS SEA TRIAL RESULTS

DIINS has been demonstrated on many sea trials. These ranged from simple data collection trials on research ships for later post-processing, to full real-time implementations on a Navy frigate in operational trials. For the designers, the best experiments are controlled trials on a dedicated research vessel, during which complete control over the trial can be maintained. In addition, post-processed DGPS reference system data set was used to generate the 'true' trajectory against which the DIINS performance could be evaluated. One such trial is detailed in [7]. While it is not possible to present all of the detail of these trials in this overview, a few representative results are shown.

The following data was collected during a real time trial of DIINS on a research vessel off the Canadian west coast in 1995. The sensor suite for that trial consisted of dual Sperry MK-29 inertial navigators, a Trimble TANS P/Y-GPS receiver and an Internav LC360 Loran-C receiver. A post processed differential GPS system was used as the reference.

The system generally performed extremely well. When P/Y GPS was available, position accuracy on the order of 5 m RMS or less was obtained (Figure 7 shows the position error from the INS1/GPS/Loran unifilter). What is more interesting is to observe the behaviour of DIINS during sensor failures. Figure 8 shows a situation when the GPS receiver fails at 1.4 hours into the plotted segment of the run. Prior to that time, the DIINS integrated position error is in the 5-6 m range (the previous figure) even though the raw unaided INS position errors are several kilometers. When the GPS fails suddenly, DIINS immediately suspends GPS measurements to all filters that use it. As can be seen, the position errors and the position error estimated standard deviation eventually grow to about 500 m, roughly the expected accuracy of the Loran system at the location of the trials.

An example of soft failure detection is shown in the subsequent figures. Figure 9 shows the raw position errors of the two INS's. It was later determined that INS2 had suffered a soft gyro failure beginning at about 1.5 hours into the run. The fault could not be picked up with the standard residual test, as shown in Figure 10. The effects of the gyro failure were gradually being distributed among all 3 gyro bias state estimates, Figure 11, (and others as well) in all the Kalman filters that used INS2. However the chi-square test statistic from the INS1 and INS2 unifilters plotted in Figure 12 clearly indicate that there is a problem in the state estimates of the filters using INS2. The chi-square test eventually fails about 2.5 hours into the runs and the SFI logic isolates the problem to INS2. The operator is notified and INS1 becomes the primary INS at that point, if it had not already been so.

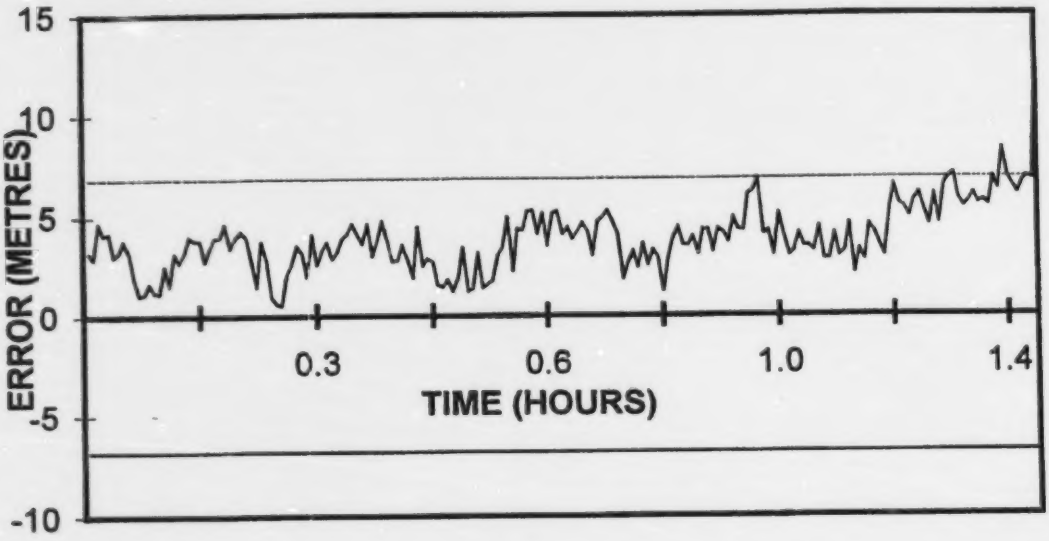

Figure 7: Typical DIINS unifilter radial position errors and 1-sigma estimates, no failures

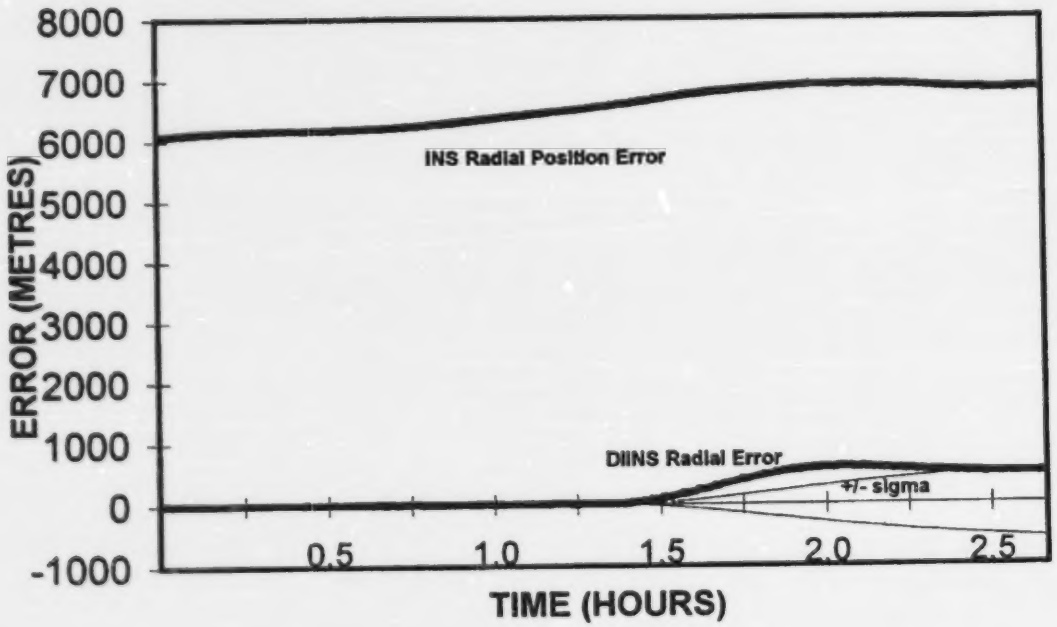

Figure 8: Graceful degradation of DIINS position errors after GPS hard fail at 1.4 hrs.

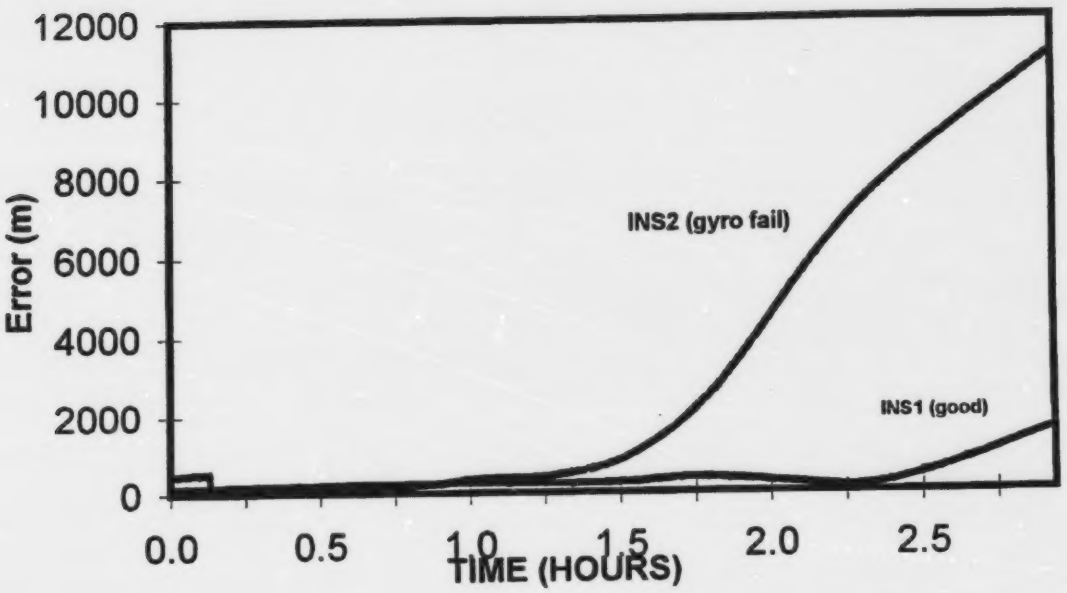

Figure 9: INS Radial position errors, INS soft fail at 1.5 hrs.

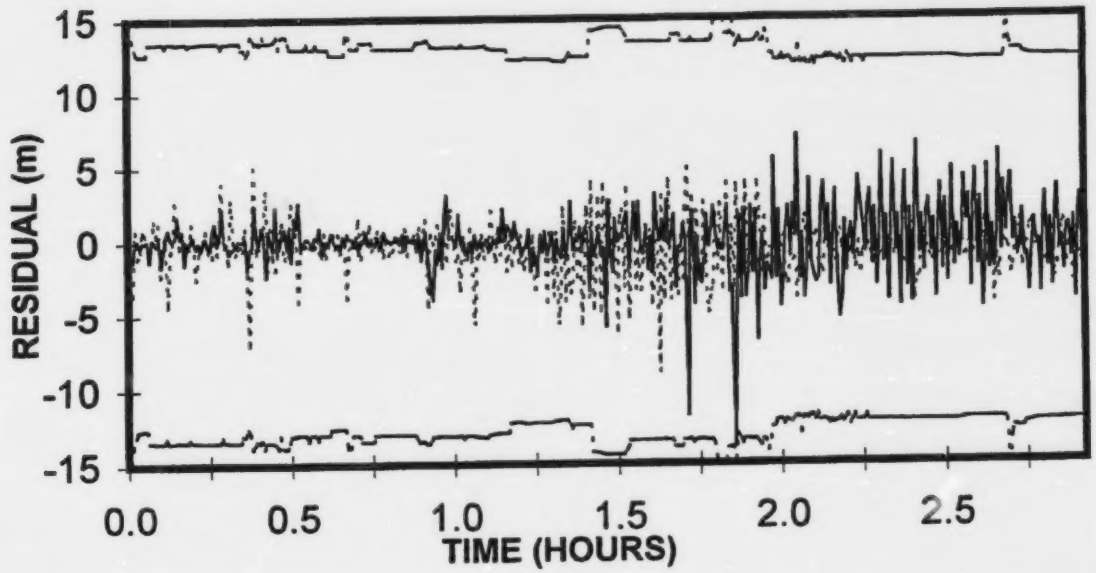

Figure 10: GPS north and east position residuals (and 5-sigma limit) from INS2 unifilter after soft fail

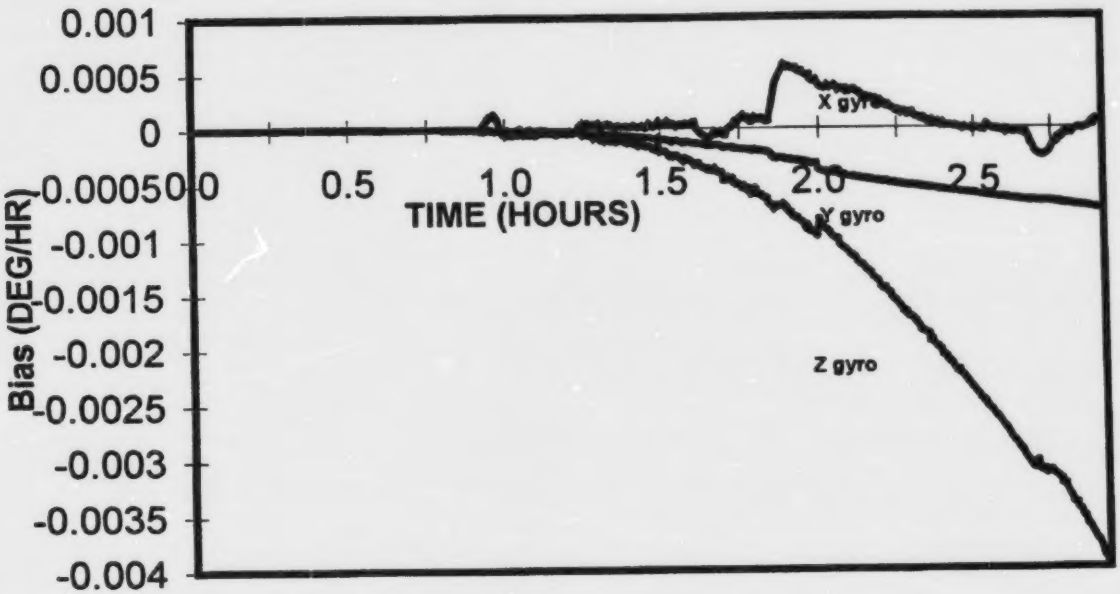

Figure 11: Gyro Bias estimates of INS2 unifilter after soft fail

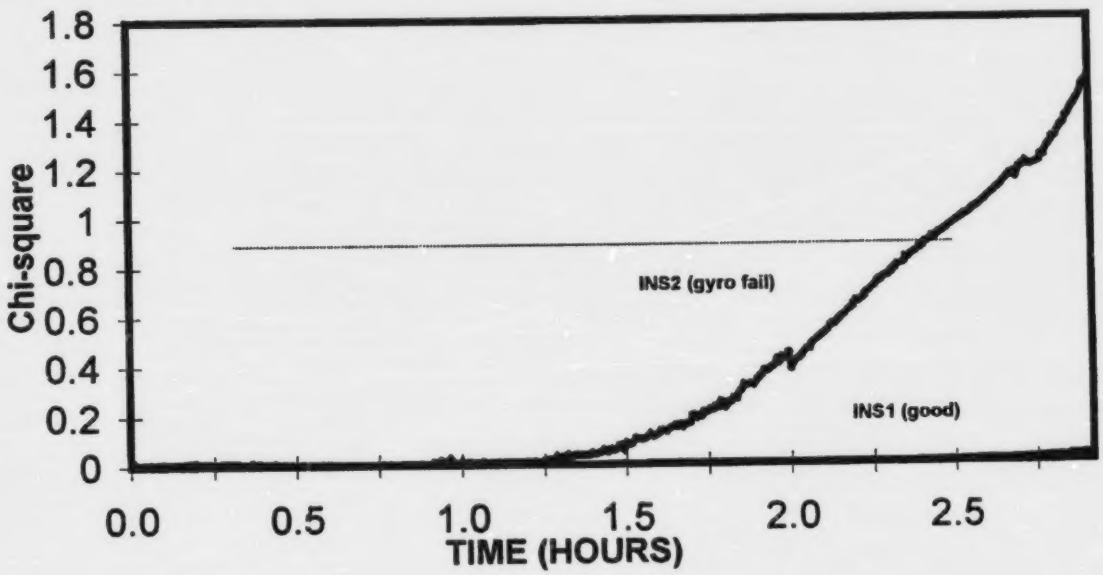

Figure 12: Normalized Chi-squared results from unifilters

7. DIINS SIMULATION SYSTEM

A DIINS simulation system was also created during the project's development. It was designed to be as flexible as possible in order to be suitable for other integrated navigation system simulations. It has been designed to exercise all of the DIINS failure modes which cannot be easily stimulated in a real sensor environment. It consists of a separate set of software programs to generate simulated trajectory data and high fidelity sensor simulators to replicate sensor performance under that trajectory and user controlled anomalies. The models are generally of higher order than the models used in the DIINS Kalman filters. For example, the INS simulator models many classical inertial errors such as sensor scale factor nonlinearities, g-sensitive drifts, misalignments, random walk and digitization effects whereas the DIINS Kalman filters effectively lump all these in an exponentially correlated bias state for each sensor with an appropriate value in the system process noise matrix ("Q" matrix). The simulated sensor data can be used in DIINS for experimentation and analysis. Similarly recorded sensor data can be post processed by DIINS. This facility has proven invaluable during the development phase. The facility can also be used to playback recorded sea trial sensor data in real-time to support end-to-end laboratory testing and post mission analysis of an operational DIINS.

8. DIINS AND THE CANADIAN NAVY

DIINS-capable SHINNADS units are being installed in the fleet in 1999 and 2000. DIINS is to undergo final trials in late 1999 and plans are being made to retrofit the SHINNADS units with the DIINS processors in 2000 or 2001. Plans are also being developed to study the feasibility of replacing the relatively simple navigation computations that presently occur within the ship's Command and Control computer system (CCS) with DIINS. This would involve software changes in the CCS to enable it to accept DIINS formatted data, and for it to allow DIINS to be "Nav Central" for the ship. An analysis of the various configuration options, operational impacts and installation costs is presently being conducted.

9. SUMMARY

This report has presented a summary of the Canadian Navy's Dual Inertial Integrated Navigation System, as developed by the Defence Research Establishment Ottawa for the Navy's patrol frigates. The underlying philosophy and design goals have been presented along with the architecture chosen to achieve them. Some of the details and results of the multi-filter implementation of that architecture have been presented along with some results from a number of controlled sea trials which demonstrate the accuracy and sensitivity of the system. The integration of the DIINS navigation computer with an ECDIS electronic chart system has demonstrated the ease of use of such a sophisticated integrated navigation system aboard a major vessel. The future plans for DIINS have been outlined.

10. REFERENCES

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APPENDIX A: DESCRIPTION OF DIINS OUTPUT DATA STREAM

1. **Introduction**: An RS232 port (default port 3) on the DIINS ADM will be used to provide serial data to user systems. This document describes the output of the DIINS ADM, software version **3.2**.

2. **Physical:** The pin-outs on the RS-232 DB9 Male Connector are standard:

1.	DCD	6.	DSR
2.	RXD	7.	RTS
3.	TXD	8.	CTS
4.	DTR	9.	NC
5.	GND		

3. **Communication Parameters**:- 19,200 baud,
   - 8 data bits, no parity, 1 stop (8N1)
   - software handshake (xon,xoff).

4. **ASCII Output Sentences**: The DIINS ADM data output will be contained in ten data sentences as follows:

a) DIINS position ($INGLL):
- Latitude
- Longitude
- time
- status
- checksum

b) DIINS heading ($INHDT):
- heading
- checksum

c) DIINS velocity, error estimate and FDIR status ($PDRO1):
- track angle COG
- ground speed SOG
- north position standard deviation estimate
- east position standard deviation estimate
- 95 percentile radial error estimate
- FDIR Status
- checksum

d) DIINS attitude ($PDRO2):
- heading
- pitch
- roll
- checksum

e) GPS (GPS_1 , GPS_2) position ($GPGGA):
- time
- Latitude
- Longitude
- quality
- HDOP
- checksum

Note: GPS_1 is Trimble P(Y), GPS_2 is DGPS

f) GPS (GPS_1 , GPS_2) velocity ($GPVTG):
- track angle COG
- ground speed SOG
- checksum

g) INS ($Mk29_1$, $Mk29_2$) position ($HEGLL):
- Latitude
- Longitude
- time
- status
- checksum

h) INS ($Mk29_1$, $Mk29_2$) heading ($HEHDT):
- heading
- checksum

i) INS ($Mk29_1$, $Mk29_2$) velocity ($HEVTG):
- track angle COG
- ground speed SOG
- checksum

j) Loran-C (LC360) position ($LCGLL):
- Latitude
- Longitude
- time
- status
- checksum

5. **Data Sentence Details**: The encapsulation of these data sets will conform to NMEA 0183 (version 2.00) where possible.

a) DIINS position data is contained in the pre-defined NMEA 0183 (version 2.00) sentence GLL. The Talker Identifier Mnemonic in this case will be IN, for Integrated Navigation.

$INGLL,llll.ll,a,yyyyy.yy,a,hhmmss.ss,A*hh<CR><LF>

llll.ll,a	WGS84 Latitude ddmm.mm,N/S
yyyyy.yy,a	WGS84 Longitude dddmm.mm,E/W
hhmmss.ss	DIINS Time of Position
A	Status (A=Valid, V=Not valid)

hh checksum

Example: $INGLL,4520.821,N,07553.328,W,150759.13,A*0E

b) DIINS heading data is contained in the NMEA 0183 (version 2.00) sentence HDT:

$INHDT,x.x,T*hh<CR><LF>

x.x,T	Heading (0-360 degrees True from North, WGS84)
hh	checksum

Example: $INHDT,248.568,T*20

c) DIINS Velocity, Error estimate and Status: Unfortunately the predefined NMEA sentence structures do not include covariance information (which is an important output of integrated navigation systems), and do not provide true velocity in a reasonable format. Therefore a custom sentence structure is defined to contain these items:

$PDRO1,x.x,T,x.x,M,x.x,N,x.x,E,x.x,C,c--c*hh<CR><LF>

where the manufacturer's Mnemonic code is DRO for Defence Research Ottawa, the 1 distinguishes this from other proprietary sentence.

x.x,T	Track angle COG (0-360 degrees True from North, WGS84)
x.x,M	Speed over ground SOG (m/s)
x.x,N	North error estimate, standard deviation (meters)
x.x,E	East error estimate, standard deviation (meters)
x.x,C	95% radial position error estimate (meters)
c---c	DIINS FDIR status word (character field)
hh	checksum

The DIINS **FDIR status word** (c---c) is a 7 character field that can be used to determine the overall health of DIINS, the current status of the individual sensors, and which DIINS internal filter is presently being used. The meaning of each digit is described here: From left to right: (Character 1 -> 1111012 <- Character 7)

Character

1 INS1 Status
  1= Used in current filter and FDI status is good
  0= Not used in current filter or FDI status is bad

2 INS2 Status
  1= Used in current filter and FDI status is good
  0= Not used in current filter or FDI status is bad

3 GPS1 Status
  1= Used in current filter and FDI status is good
  0= Not used in current filter or FDI status is bad

4 GPS2 Status
  1= Used in current filter and FDI status is good

0= Not used in current filter or FDI status is bad

5 Loran Status
1= Used in current filter and FDI status is good
0= Not used in current filter or FDI status is bad

6 DIINS Overall Health
1=At least one valid integrating filter,
0=No valid INS or Kalman filter. Best Single sensor is being output

7 Which internal Filter is currently selected for output
1 through F (hex)

Example: $PDRO1,41.466,T,0.009,M,3.1,N,3.1,E,7.6,C,0111113*60

d) DIINS Attitude: The predefined NMEA sentence structures do not include attitude information. Therefore a second proprietary sentence structure is defined:

$PDRO2,x.x,x.x,x.x*hh<CR><LF>

where from left to right,

x.x, Heading (deg), deg from North True (0-360)

x.x, Pitch (deg). Bow down positive (USN convention. DIINS internal convention is bow up positive)

x.x Roll (deg). Starboard up positive (USN convention. DIINS internal convention is starboard down positive)

Example: $PDRO2,248.563,-0.662,0.387*14

e) GPS Position: For the GPS data the GGA sentence will be used (possibly with null fields).

$GPGGA,hhmmss.ss,llll.ll,a,yyyyy.yy,a,q,nn,d.d,x.x,M,x.x,M,x.x,xxxx*hh<CR><LF>

hhmmss.ss	UTC Time of Position
llll.ll,a	WGS84 Latitude ddmm.mm,N/S
yyyyy.yy,a	WGS84 Longitude dddmm.mm,E/W
q,	GPS Quality 0 = Fix not available or not valid (From sensor DCT) 1 = GPS fix valid 2 = DGPS SPS mode, fix valid **[May not be present]** 3 = GPS PPS mode, fix valid **[May not be present]**
nn,	number of satellites in view **[May be null]**
d.d	HDOP
(Rest of fields may be null)	
hh	checksum

Example: $GPGGA,150801.01,4520.821,N,07553.326,W,1,,1.0,,,,,,*48

f) GPS Velocity: For the GPS velocity data the VTG sentence will be used:

$GPVTG,x.x,T,x.x,M,x.x.N,x.x,K*hh<CR><LF>

x.x,T	Track angle COG (0-360 degrees True from North, WGS84)
x.x,M	Track angle COG (degrees Magnetic) **[May be Null]**
x.x,N	Speed over ground (knots)
x.x,K	Speed over ground (km/hr)
hh	checksum

Example: $GPVTG,263.000,T,,M,0.053996,N,0.100000,K*66

NOTE 1: To identify which GPS the $GPGGA and $GPVTG data comes from (i.e. GPS1 or GPS2), each pair of these messages will always be preceded with the appropriate STN sentence:

$GPSTN,xx*hh<CR><LF>

where xx is either 01 or 02.

NOTE 2: The $GPSTN, $GPGGA, $GPVTG sentences will always appear as a set corresponding to one or the other of the GPS's. That is, there will be a set of sentences in the order ($GPSTN,01 ... $GPGGA .... GPVTG) corresponding to GPS1 and another set ($GPSTN,02 ... $GPGGA .... $GPVTG) corresponding to GPS2. These sets of sentences will not be intermixed with each other, although other sentences (particularly the high rate $PDR02) may be intermixed with them.

g) INS Position: The Inertial position data will be contained in the approved GLL sentence format. There is no INS "Talker Mnemonic", however HE comes close.

$HEGLL,llll.ll,a,yyyyy.yy,a,hhmmss.ss,A*hh<CR><LF>

llll.ll,a	Latitude ddmm.mm,N/S
yyyyy.yy,a	Longitude dddmm.mm,E/W
hhmmss.ss	DIINS Time of Position
A	Status (A=Valid, V=Not valid) from sensor DCT
hh	checksum

Example: $HEGLL,4520.916,N,07553.050,W,154247.19,A*09

h) INS Heading: The Inertial heading data will be contained in the HDT sentence format.

$HEHDT,x.x,T*hh<CR><LF>

x.x,T	Heading (0-360 degrees True from North)
hh	checksum

Example: $HEHDT,248.566,T*24

i) INS Velocity: The Inertial course and speed data will be contained in the approved VTG sentence format.

$HEVTG,x.x,T,x.x,M,x.x.N,x.x,K*hh<CR><LF>

x.x,T	Track angle or CMG (0-360 degrees True from North, WGS84)	
x.x,M	Track angle or CMG (degrees Magnetic)	**[May be Null]**
x.x,N	Speed (knots)	
x.x,K	Speed (km/hr)	
hh	checksum	

Example: $HEVTG,95.194,T,,M,0.043146,N,0.079906,K*4F

NOTE 1: To identify which INS the $HEGLL, $HEHDT and $HEVTG data comes from (i.e. INS1 or INS2), each set of these messages will always be preceded with the appropriate STN sentence:

$HESTN,xx*hh<CR><LF>

where xx is either 01 or 02.

NOTE 2: The $HESTN, $HEGLL, $HEHDT, $HEVTG sentences will always appear as a set corresponding to one or the other of the INS's. That is, there will be a set of sentences in the order ($HESTN,01 ... $HEGLL .... $HEHDT…$HEVTG) corresponding to INS1 and another set ($HESTN,02 ... $HEGLL .... $HEHDT…$HEVTG) corresponding to INS2. These sets of sentences will not be intermixed with each other, although other sentences (particularly the high rate $PDR02) may be intermixed with them.

j) Loran-C position data will be contained in the approved GLL sentence format:

$LCGLL,llll.ll,a,yyyyy.yy,a,hhmmss.ss,A*hh<CR><LF>

llll.ll,a	WGS84 Latitude ddmm.mm,N/S
yyyyy.yy,a	WGS84 Longitude dddmm.mm,E/W
hhmmss.ss	DIINS Time of Position
A	Status (A=Valid, V=Not valid) from Sensor DCT
hh	checksum

Example: $LCGLL,4520.467,N,07552.967,W,154257.49,A*08

6. **Output Rates**:

INS sentences ($HEGLL(5.g), $HEHDT(5.h) and $HEVTG(5.i)) are output every 1.28 seconds

DIINS sentences ($INGLL(5.a), $INHDT(5.b), $PDRO1(5.c)) are output at an integer multiple of 1.28 seconds (ranging from 1 to 7 depending on the configuration).

Attitude data sentence ($PDRO2(5.d)) is output every 80 milliseconds.

GPS ($GPGGA(5.e), $GPVTG(5.f)) and Loran ($LCGLL(5.j)) sentences will be output as available (approximately every second).

7. **Sample Output**: The following is a sample of DIINS output :

```
$HESTN,01*69
$HEGLL,4522.589,N,07551.267,W,154254.47,A*0C
$HEHDT,246.857,T*25
$HEVTG,53.448,T,,M,0.846107,N,1.566990,K*4C
$PDRO2,248.559,-0.657,0.381*1D
$PDRO2,248.565,-0.662,0.384*11
$PDRO2,248.559,-0.657,0.384*18
$PDRO2,248.565,-0.659,0.381*1C
$PDRO2,248.559,-0.654,0.384*1B
$HESTN,02*6A
$HEGLL,4520.916,N,07553.050,W,154245.91,A*0B
$HEHDT,248.566,T*24
$HEVTG,101.310,T,,M,0.039836,N,0.073776,K*7D
$PDRO2,248.559,-0.657,0.384*18
$PDRO2,248.565,-0.657,0.376*1A
$PDRO2,248.559,-0.657,0.381*1D
$PDRO2,248.565,-0.662,0.381*14
$PDRO2,248.559,-0.662,0.384*1E
$PDRO2,248.565,-0.654,0.384*14
$HESTN,01*69
$HEGLL,4522.589,N,07551.267,W,154255.75,A*0C
$HEHDT,246.863,T*22
$HEVTG,53.393,T,,M,0.851571,N,1.577110,K*4E
$PDRO2,248.559,-0.659,0.384*16
$GPSTN,02*70
$GPGGA,154256.26,4520.822,N,07553.328,W,2,,2.4,,,,,,*48
$GPVTG,0.000,T,,M,0.021598,N,0.040000,K*63
$PDRO2,248.559,-0.657,0.384*18
$LCGLL,4520.467,N,07552.967,W,154256.51,A*00
$PDRO2,248.559,-0.654,0.381*1E
$PDRO2,248.565,-0.657,0.384*17
$PDRO2,248.559,-0.657,0.384*18
$PDRO2,248.565,-0.657,0.384*17
$PDRO2,248.565,-0.657,0.381*12
$PDRO2,248.565,-0.657,0.384*17
$PDRO2,248.559,-0.657,0.384*18
$PDRO2,248.559,-0.654,0.381*1E
$HESTN,02*6A
$HEGLL,4520.916,N,07553.050,W,154247.19,A*09
$HEHDT,248.566,T*24
$HEVTG,95.194,T,,M,0.043146,N,0.079906,K*4F
$PDRO2,248.559,-0.657,0.381*1D
```

$PDRO2,248.565,-0.659,0.384*19
$PDRO2,248.565,-0.657,0.384*17
$PDRO2,248.559,-0.662,0.381*1B
$PDRO2,248.559,-0.654,0.381*1E
$PDRO2,248.559,-0.657,0.381*1D
$PDRO2,248.559,-0.662,0.381*1B
$PDRO2,248.559,-0.654,0.384*1B
$GPSTN,01*73
$GPGGA,154257.00,4520.822,N,07553.330,W,1,,1.0,,,,,,*40
$GPVTG,263.000,T,,M,0.053996,N,0.100000,K*66
$HESTN,01*69
$HEGLL,4522.589,N,07551.267,W,154257.03,A*0F
$HEHDT,246.863,T*22
$HEVTG,53.604,T,,M,0.849248,N,1.572807,K*4B
$PDRO2,248.565,-0.657,0.376*1A
$GPSTN,02*70
$GPGGA,154257.26,4520.822,N,07553.328,W,2,,2.4,,,,,,*49
$GPVTG,0.000,T,,M,0.026998,N,0.050000,K*69
$LCGLL,4520.467,N,07552.967,W,154257.49,A*08
$INGLL,4520.823,N,07553.328,W,154247.19,A*08
$INHDT,248.559,T*22
$PDRO1,35.253,T,0.040,M,2.6,N,2.6,E,6.4,C,0111113*6D
$PDRO2,248.565,-0.662,0.381*14
$PDRO2,248.559,-0.654,0.381*1E
$PDRO2,248.565,-0.657,0.384*17
$PDRO2,248.565,-0.654,0.384*14
$PDRO2,248.559,-0.654,0.381*1E
$PDRO2,248.559,-0.657,0.384*18
$PDRO2,248.565,-0.654,0.381*11
$HESTN,02*6A
$HEGLL,4520.916,N,07553.050,W,154248.47,A*0D
$HEHDT,248.571,T*22
$HEVTG,100.305,T,,M,0.043673,N,0.080883,K*73
$PDRO2,248.565,-0.657,0.384*17
$PDRO2,248.565,-0.657,0.384*17
$PDRO2,248.565,-0.657,0.384*17
$PDRO2,248.559,-0.654,0.381*1E
$PDRO2,248.565,-0.657,0.384*17
$PDRO2,248.559,-0.662,0.381*1B
$PDRO2,248.559,-0.654,0.384*1B
$PDRO2,248.559,-0.659,0.384*16
$GPSTN,01*73
$GPGGA,154258.00,4520.822,N,07553.330,W,1,,1.0,,,,,,*4F
$GPVTG,318.000,T,,M,0.053996,N,0.100000,K*6B
$PDRO2,248.565,-0.657,0.381*12
$GPSTN,02*70
$GPGGA,154258.26,4520.822,N,07553.328,W,2,,2.4,,,,,,*46
$GPVTG,0.000,T,,M,0.021598,N,0.040000,K*63
$PDRO2,248.565,-0.657,0.376*1A
$PDRO2,248.559,-0.657,0.381*1D
$PDRO2,248.565,-0.654,0.379*16
$HESTN,01*69
$HEGLL,4522.589,N,07551.266,W,154258.31,A*00
$HEHDT,246.868,T*29
$HEVTG,53.393,T,,M,0.851571,N,1.577110,K*4E
$PDRO2,248.559,-0.654,0.379*19
$PDRO2,248.559,-0.657,0.384*18
$PDRO2,248.565,-0.657,0.384*17
$PDRO2,248.559,-0.659,0.387*15

APPENDIX B: SHINNADS DISPLAY of DIINS DATA

This table is used to determine which fields (indicated as underlined) of the DIINS data sentences are used to drive the corresponding area on the SHINNADS display screen. The column on the right indicates the units in which the data is transmitted (and not necessarily what is displayed on the SHINNADS screen).

SHINNADS DISPLAY AREA	Info obtained from	Units
DIINS SOLUTION:		
Latitude	$INGLL,llll.ll,a,yyyyy.yy,a,hhmmss.ss,A	ddmm.mmm
Longitude	$INGLL,llll.ll,a,yyyyy.yy,a,hhmmss.ss,A	dddmm.mmm
heading	$INHDT,x.x,T	deg
COG	$PDRO1,x.x,T,x.x,M,x.x,N,x.x,E,x.x,C,cccccc	deg
SOG	$PDRO1,x.x,T,x.x,M,x.x,N,x.x,E,x.x,C,cccccc	m/s
Est.Error (95%)	$PDRO1,x.x,T,x.x,M,x.x,N,x.x,E,x.x,C,cccccc	meters
North st.dev.	$PDRO1,x.x,T,x.x,M,x.x,N,x.x,E,x.x,C,cccccc	meters
East st. dev.	$PDRO1,x.x,T,x.x,M,x.x,N,x.x,E,x.x,C,cccccc	meters
DIINS STATUS:		
Status	$PDRO1,x.x,T,x.x,M,x.x,N,x.x,E,x.x,C,ccccccc	0 or 1

NOTE: The overall DIINS status is displayed as "Good" if this character equals 1, and "Single Sensor" if it equals 0.

Currently Integrating		
INS1 ?	$PDRO1,x.x,T,x.x,M,x.x,N,x.x,E,x.x,C,ccccccc	0 or 1
INS2 ?	$PDRO1,x.x,T,x.x,M,x.x,N,x.x,E,x.x,C,ccccccc	0 or 1
GPS1 ?	$PDRO1,x.x,T,x.x,M,x.x,N,x.x,E,x.x,C,ccccccc	0 or 1
GPS2 ?	$PDRO1,x.x,T,x.x,M,x.x,N,x.x,E,x.x,C,ccccccc	0 or 1
Loran ?	$PDRO1,x.x,T,x.x,M,x.x,N,x.x,E,x.x,C,ccccccc	0 or 1

NOTE: The sensors listed in the "Currently Integrating" box are the ones that have the above underlined corresponding "used" character above equal to 1

Raw Data

GPS1 (TANS P(Y)):

$GPSTN,01 then

Latitude	$GPGGA,hhmmss.ss,llll.ll,a,yyyyy.yy,a,q,nn,d.d,x.x,,,,,,	ddmm.mmm
Longitude	$GPGGA,hhmmss.ss,llll.ll,a,yyyyy.yy,a,q,nn,d.d,x.x,,,,,,	dddmm.mmm
Heading	N/A	---
SOG	$GPVTG,x.x,T,x.x,M,x.x.N,x.x,K	km/hr

COG	$GPVTG,x.x,T,x.x,M,x.x.N,x.x,K	deg
Status	$PDRO1,x.x,T,x.x,M,x.x,N,x.x,E,x.x,C,ccccccc	1=Used 0=Ignored

GPS2 (DGPS):

$GPSTN,02 then

Latitude	$GPGGA,hhmmss.ss,llll.ll,a,yyyyy.yy,a,q,nn,d.d,,,,,,	ddmm.mmm
Longitude	$GPGGA,hhmmss.ss,llll.ll,a,yyyyy.yy,a,q,nn,d.d,,,,,,	dddmm.mmm
Heading	N/A	---
SOG	$GPVTG,x.x,T,x.x,M,x.x.N,x.x,K	km/hr
COG	$GPVTG,x.x,T,x.x,M,x.x.N,x.x,K	deg
Status	$PDRO1,x.x,T,x.x,M,x.x,N,x.x,E,x.x,C,ccccccc	1=Used 0=Ignored

INS1 (Mk29 FORE):

$HESTN,01 then

Latitude	$HEGLL,llll.ll,a,yyyyy.yy,a,hhmmss.ss,A	ddmm.mmm
Longitude	$HEGLL,llll.ll,a,yyyyy.yy,a,hhmmss.ss,A	dddmm.mmm
Heading	$HEHDT,x.x,T	deg
SOG	$HEVTG,x.x,T,x.x,M,x.x.N,x.x,K	km/hr
COG	$HEVTG,x.x,T,x.x,M,x.x.N,x.x,K	deg
Status	$PDRO1,x.x,T,x.x,M,x.x,N,x.x,E,x.x,C,ccccccc	1=Used 0=Ignored

INS2 (Mk29 AFT):

$HESTN,02 then

Latitude	$HEGLL,llll.ll,a,yyyyy.yy,a,hhmmss.ss,A	ddmm.mmm
Longitude	$HEGLL,llll.ll,a,yyyyy.yy,a,hhmmss.ss,A	dddmm.mmm
Heading	$HEHDT,x.x,T	deg
SOG	$HEVTG,x.x,T,x.x,M,x.x.N,x.x,K	km/hr
COG	$HEVTG,x.x,T,x.x,M,x.x.N,x.x,K	deg
Status	$PDRO1,x.x,T,x.x,M,x.x,N,x.x,E,x.x,C,ccccccc	1=Used 0=Ignored

LORAN-C (LC360):

Latitude	$LCGLL,llll.ll,a,yyyyy.yy,a,hhmmss.ss,A	ddmm.mmm
Longitude	$LCGLL,llll.ll,a,yyyyy.yy,a,hhmmss.ss,A	dddmm.mmm
Heading	N/A	---
SOG	N/A	---
COG	N/A	---

Status	$PDRO1,x.x,T,x.x,M,x.x,N,x.x,E,x.x,C,ccccccc	1=Used 0=Ignored
TIME:	$INGLL,llll.ll,a,yyyyy.yy,a,hhmmss.ss,A	